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RESEARCH MEMORANDUM

AN INVESTIGATION OF THE EFFECTS OF RAPID SKIN HEATING ON BOX BEAMS LOADED IN BENDING

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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AN INVESTIGATION OF THE EFFECTS OF RAPID SKIN HEATING ON BOX BEAMS LOADED IN BENDING

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SUMMARY

Two beams of each of three web types were loaded in bending and subjected to rapid skin heating at rates of about 50° F to 70° F per second. Skin buckling which was predicted by a simplified analysis occurred in channel-web beams because of thermal stresses superimposed on bending stresses. Large bending deflections under constant load followed skin buckling. Buckling due to thermal stresses did not occur when the supporting web structure was changed to either corrugated webs or truss webs. In spite of large variations in buckling effects, thermal stresses appeared to have little influence on failing strength. All three beam types underwent approximately the same percentage reduction in failing strength which was primarily due to deterioration in material properties with temperature.

INTRODUCTION

The behavior of aircraft structures subjected to rapid heating is a problem of increasing concern to the designer. For example, when the skin of a conventional wing is heated rapidly, thermal stresses develop because of the restraints imposed by the colder internal structure and material properties may change rapidly with the increase in temperature. Prediction of structural behavior under such conditions is at present highly approximate.

The experimental investigation reported herein was undertaken in order to explore some of the effects which rapid skin heating would have on the buckling and failing strength of multiweb-wing structures. Comparisons are made of the buckling and failing stresses for beams fabricated with three types of web structure: channel webs which induce thermal stresses under conditions of rapid skin heating, and corrugated and truss webs both of which represent interior structures that minimize resistance to thermal expansion of the skin.

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SYMBOLS

A_S	cross-sectional area of one skin, in.^{2}
A_W	one-half total cross-sectional area of webs, in.^{2}
E_S	modulus of elasticity of skin material, ksi
E_W	modulus of elasticity of web material, ksi
σ_b	stress in skin produced by external bending moment, ksi
σ_{cr}	buckling stress of skin, ksi
σ_T	average thermal stress in skin, ksi
ΔT	average temperature difference between skin and webs, $^{\circ}F$
α	thermal coefficient of expansion, in./in./$^{\circ}F$

DESCRIPTION OF SPECIMENS

All specimens were one-cell beams fabricated with skins of clad 2024-T3 aluminum-alloy sheet (previously designated 24S-T3) 0.125 inch thick and were designed to develop a room-temperature failing strength of approximately 30 ksi in pure bending.

Three channel-web beams were fabricated by riveting formed channels to skins through an attachment flange made by cold bending the web material. (See fig. 1.)

Standard clad 2024-T4 aluminum-alloy corrugated sheet was utilized in the three corrugated-web beams. (See fig. 2.) Webs were attached to skin by clip angles, one clip on each corrugation crest inside or out.

Three truss-web beams were fabricated by riveting tee-connections to the skin at each panel point (fig. 3). The 2024-T4 aluminum-alloy truss members were bolted to the stems of each tee to provide a pinned connection. Panel point spacing was designed to prevent Euler column failure in the skin between panel points until a skin stress of approximately 30 ksi was developed at room temperature.

All three beams were designed to have the same width of skin (5 inches) between supports. In the channel-web beam, this skin width was selected as the distance between points midway between web and rivet center lines (fig. 1). In the corrugated- and truss-web beams, however, the skin width was selected as the distance between web center lines because the web-skin connections are symmetrical.

In order to evaluate the behavior of the three types of beams when loaded in pure bending, room-temperature strength tests were run. The average stresses in the skin at buckling and at failure are given in table I. Local buckling of the compression skin was observed in all three beams. Beam failure occurred in the compression skin in a mode different from the initial buckling; the channel-web beam developed a narrow wrinkle which crushed the webs in the vicinity of the flanges, the corrugated-web beam developed a wrinkle which pulled the skin away from the webs breaking several attachment angles, and the truss-web beam developed a column failure in the compression skin between two truss panel points.

Elastic beam stiffnesses were checked experimentally by both strain and deflection measurements. These tests verified that the corrugated and truss webs contribute nothing to the beam moment of inertia because of their negligible axial stiffness. Shear-stiffness tests indicated that the corrugated-web beam had only about 50 percent of the shear stiffness of an equivalent flat plate and the truss-web beam had only about 10 percent. This low value for the truss-web beam is due to the combined effect of looseness in the truss joints and the steep angle of inclination of the truss members.

TEST PROCEDURES

Facilities

Two beams of each web type were subjected to combinations of static bending moment and rapid skin heating. Static bending moment was applied to a specimen cantilevered to a rigid support (see fig. 4) by a loading frame consisting of a weight cage and a system of bars, pivots, and rollers that permitted the specimen tip to rotate and translate freely while maintaining a constant bending moment.

Rapid heating of both cover skins of the beams was accomplished by carbon-rod radiators which supplied a source of high-intensity heat throughout the center portion of the specimen length. Each radiator consisted of nine $\frac{3}{8}$-inch-diameter carbon rods 20 inches long placed side by side and parallel to the length of the beam at a 1 inch spacing.

The carbon rods were heated to incandescence by passing approximately 300 kilowatts of power through the rods. An asbestos shield then was quickly removed from between the radiators and specimen so that the skins were exposed to the incandescent rods.

In all cases heating was applied until failure or until the thermocouple in the center of the compression skin indicated a temperature of about 600° F. The test time varied from about 7 to 13 seconds. The specimen skins were painted black to increase the heating rate; a maximum heating rate of 29 Btu/sq ft/sec could be obtained. This heating rate corresponds to a skin-temperature rise of 72° F per second in these beams. Deterioration of the carbon rods with heating time caused a decrease in their heat output so that use of the same rods for more than one test produced lower heating rates. The rods were replaced whenever their output dropped to about two-thirds of their initial output.

The radiator assembly was supported on the specimen with its weight counterbalanced so that the radiators followed the specimen as it deflected. Corresponding points on both skins of any specimen were within 5 percent of the same temperature increase at any time and the temperature variation along a 12-inch length in midspan was within ±5 percent of the mean temperature.

Instrumentation

Twelve thermocouples were located in the test section of each beam; three in each skin along a spanwise center line and six at the center cross section. Thermocouple beads of iron-constantan wire (no. 24 gage) were peened into small holes drilled in the sheet material and the resultant assemblies were spot welded to obtain a good contact between the thermocouple and the sheet material. Thermocouple output was recorded on an oscillograph recorder as a function of time. Estimated probable errors of temperature were ±3° F.

During the test, tip deflection of the test specimens was measured by recording the strain measured at the root of a flexible cantilever based on a reference plane and connected to the specimen tip fixture by taut wire. This strain was recorded on the same recorder as the thermocouples.

RESULTS AND DISCUSSION

Two beams of each web type were failed under various combinations of static bending load and rapid skin heating as detailed in table II. Because these were exploratory tests, the static loads were varied from test to test principally on the basis of the preceding tests. It was attempted to limit the heating so that maximum indicated skin temperature would not exceed 600° F. As given in table II, maximum skin temperatures of about 600° F were achieved in most cases unless failure occurred prior to 600° F. Overheating occurred several times when the shield jammed while being interposed between the specimen and the radiators. Detailed behavior of each beam is given in the following section.

Beam Behavior

Channel-web beam 1.- The initial static bending stress for this beam was 9.8 ksi which is about two-thirds of the predicted strength for the beam at 600° F for 1/2 hour before loading. It was anticipated that the combined thermal stresses and bending stresses would produce failure.

Thermal stresses did develop as the beam was heated and buckling of the compression skin occurred at an average skin temperature of 375° F. Buckling was detected by the abrupt change in rate of growth of tip deflection with heating as shown in figure 5. Continuation of the heating after buckling caused the beam deflections to grow rapidly but failure had not occurred when heating was terminated at an average skin temperature of 547° F. As the beam cooled off, the contraction of the buckled skin created sufficient compression to produce web buckling. Thus, after completion of the first heating cycle, deep buckles were present in both the skin and the webs and a permanent deflection remained.

In order to study whether the deformations would grow, the heating cycle was repeated with the same bending stress until 12 cycles had been applied. After the second cycle (in which overheating occurred), the permanent deformation remained essentially constant. Elastic deformations occurred in each cycle because of variation in the material elastic modulus.

After the twelfth cycle, the bending stress was increased incrementally with each heating cycle (table II) and the permanent deformations grew with each application of rapid heating until failure occurred with a bending stress in the skin of 22 ksi and an average skin temperature of 453° F. The failure mode was similar to the room-temperature failure in that the compression skin crushed the webs in the vicinity of the attachment flanges in a narrow wrinkle. Photographs of rapid-heating and room-temperature failures are shown in figure 6.

Channel-web beam 2.- In order to investigate possible reduction in the failing strength due to the thermal cycling of channel-web beam 1, channel-web beam 2 was statically loaded to a skin stress of 22 ksi. When subjected to rapid heating, skin buckling occurred when the average skin temperature reached 165° F and failure occurred when the heating cycle reached its peak value with the average skin temperature at 511° F, thus, a reduction in strength from the thermal cycling was indicated. Again, a rapid growth of beam deflection was noted when heating was continued after buckling. Variation of temperature at failure in the center cross section is shown in figure 7.

Corrugated-web beam 1.- Corrugated-web beam 1 was loaded statically to a skin stress of 26 ksi before heating; this stress is the same percentage of room-temperature failing stress as the channel-web beams carried.

Failure occurred during the first cycle of rapid skin heating at an average skin temperature of 520° F which is comparable to the 511° F at failure in the second channel-web beam. No evidence of buckling prior to failure was observed either visibly or by abrupt changes in growth of the tip deflection. Tip deflections increased with temperatures as a result of a decrease in material modulus. At failure the compression skin developed a wrinkle which pulled away from the webs and broke attachment angles and rivet heads. This type of failure is similar to the room-temperature failure as is shown in figure 8.

Corrugated-web beam 2.- Corrugated-web beam 2 was tested at the same bending stress as channel-web beam 2 to determine the maximum temperature at which it can carry the same stress (22 ksi). Failure occurred in the same manner as that for corrugated-web beam 1 but with a static skin stress of 22 ksi and at an average skin temperature of 546° F. Variation of temperature in the center cross section at the time of failure is shown in figure 9. At this stress level the corrugated-web beam failed at only slightly greater temperatures than the channel-web beam even though no buckling occurred, possibly because material properties are changing rapidly.

Truss-web beam 1.- Truss-web beam 1 was initially loaded to 10 ksi. It showed no signs of buckling when heated rapidly. The bending stress was increased to 22 ksi for the next test. During application of load the skin buckled elastically at its room-temperature buckling value (19 ksi).

When the average skin temperature reached 457° F, column-type failure of the compression skin occurred between truss panel points in the same manner as that for the room-temperature failure. (See fig. 10.) This failing temperature was lower than those for the channel-web beam 2 and corrugated-web beam 2, both of which were carrying the same skin stress. Variation of temperature in the center cross section at the time of failure is shown in figure 11.

Truss-web beam 2.- Truss-web beam 2 was subjected to cycles of rapid heating at bending stresses varying from 15 ksi to 20 ksi. Skin buckling occurred during the first cycle of heating at an average temperature of 440° F. This effect was due to a change in elastic modulus and not to thermal stress as is discussed in the following section. Buckling was not too clearly defined for either truss-web beam because of the large initial waviness in both skins that resulted from looseness in the truss connections.

The static skin stress was increased incrementally with each succeeding cycle of rapid heating (table II) and, as a result, permanent buckle deformation and beam deflection increased. Failure occurred with a stress of 20 ksi and at an average skin temperature of 508° F.

Analysis

Skin buckling.- The stress required to buckle the skin of beams such as were tested in this program can be calculated as a function of the beam geometry, the support supplied to the skin by the webs, and the material modulus which is a function of temperature. It is assumed that at the time of buckling the stress required for buckling will be the sum of the applied bending stress and the average thermal stress in the skin. Although the actual thermal stresses in the skin follow a gradient similar to the gradient in temperature across the skin, variations between the gradient stress and the average value were small in comparison with the average stress produced by the heating rates used in this investigation.

Thus at buckling,

$$\sigma_b + \sigma_T = \sigma_{cr} \tag{1}$$

From an elementary stress analysis including thermal expansion and if complete continuity between the skin and the webs is assumed,

$$\sigma_T = \frac{\alpha E_S \, \Delta T}{1 + \frac{E_S A_S}{E_W A_W}} \tag{2}$$

Combining equations (1) and (2) the relationship between bending stress and average-temperature difference required to produce skin buckling can be written as

$$\Delta T = \left(\sigma_{cr} - \sigma_b\right) \frac{1 + \frac{E_S A_S}{E_W A_W}}{\alpha E_S} \tag{3}$$

Comparison of average-temperature differences observed experimentally when buckling occurred in the two channel-web beams with those calculated from equation (3) is shown in figure 12. The curve was calculated on the assumption that web material properties were the same as those at room temperature, but the skin elastic modulus varied with the average skin temperature. Changes in modulus with temperature were taken from figure 5 of reference 1.

The experimental temperature difference between skin and webs (fig. 12) was taken from average temperatures for each element. Figure 13 shows the temperature distribution at the center cross section in the two channel-web beams when buckling occurred. Average temperature of skin or of webs was computed from a smooth-curve distribution through the points at which temperature was measured.

The correlation between the calculated curve and experimental values of ΔT at buckling shown in figure 12 indicates that the elementary buckling analysis presented here is adequate for the heating rates used.

After buckling of one skin surface of the beam, an unsymmetrical structure was created. Further heating of this unsymmetrical structure produced bending deflections. In this beam these deflections were larger than the changes in deflection produced by deterioration in material properties with temperature. (See fig. 5.)

In the corrugated-web beams the absence of detectable skin buckling indicated that no appreciable thermal stresses could have developed. Calculated buckling stresses based on reduced elastic moduli at the failing temperatures indicated that buckling could have occurred because of applied bending stress alone.

Buckling of truss-web beam 2 with a bending stress of 15 ksi can also be attributed to the reduction in elastic modulus with increasing temperature. To reduce the buckling stress from 19.1 ksi to 15 ksi would require a 22-percent change in modulus which for 2024-T3 aluminum alloy corresponds to a temperature of about 525° F (ref. 1). Experimentally the average skin temperature was 439° F with a peak value of 488° F in the center when the beam buckled.

Beam failure.- Three of the six beam failures occurred at approximately the same average skin temperature; 511° F, 520° F, and 508° F (table II) for a channel-web beam, a corrugated-web beam, and a truss-web beam, respectively, or an average of 513° F. These three beams represented three types of construction; one which developed thermal stresses large enough to produce severe skin buckling and two which were nearly thermal stress free. Each beam, however, was carrying a bending stress at failure of approximately 73 percent of the corresponding beam-failure stress at room temperature. This condition would indicate that the effects of rapid skin heating on the failure of the three beam types was essentially the same and was due primarily to a deterioration of material properties. In the large redistribution of stresses after buckling in the channel-web beams, the superimposed thermal stresses appear to have a negligible effect on failure.

CONCLUDING REMARKS

The following observations are made from the results of the present tests on six beams loaded to failure by a combination of applied bending moment and rapid skin heating at rates of about 50° F to 70° F per second.

Skin buckling in beams with channel webs was produced by combinations of bending stress and thermal stress resulting from rapid heating. These combinations were predicted from a simplified analysis for the heating rates used. The occurrence of skin buckling in beams with channel webs led to large increases in bending deflection with further heating under constant load. Skin buckling due to thermal stresses did not occur when the supporting web structure was changed from channel webs to either corrugated webs or truss webs.

Thermal stresses appeared to have little influence on beam strength. The three beam types, channel web, corrugated webs, and truss webs, which developed thermal stresses of widely varying magnitude, underwent approximately the same percentage reduction in failing strength when heated rapidly to the same skin temperature. This loss in failing strength can be attributed to reduction in material properties with elevated temperature.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 18, 1955.

REFERENCE

1. Roberts, William M., and Heimerl, George J.: Elevated-Temperature Compressive Stress-Strain Data for 24S-T3 Aluminum-Alloy Sheet and Comparisons With Extruded 75S-T6 Aluminum Alloy. NACA TN 1837, 1949.

TABLE I.- ROOM-TEMPERATURE BUCKLING AND FAILING STRESSES

IN COMPRESSION SKIN OF BOX BEAMS

Beam	Buckling stress, ksi	Average stress at failure, ksi
Channel-web	24.5	29.7
Corrugated-web	31.0	35.2
Truss-web	19.1	27.7

[redacted]

TABLE II.- COMBINATIONS OF BENDING STRESS AND RAPID SKIN

HEATING APPLIED TO BOX BEAMS

Beam	Test	Bending stress, ksi	Skin temperature at peak of heating cycle		Heating time, sec	Rate of skin heating,[c] °F/sec
			Maximum, °F	Average, °F		
Channel-web beam 1	1	9.8	611	547	8.0	66
	2	9.8	710	647	10.7	59
	3	9.8	580	524	8.2	61
	4	9.8	640	587	9.4	59
	5	9.8	678	610	11.0	54
	6	9.8	692	617	12.7	48
	7	9.8	657	593	11.1	52
	8	9.8	615	565	10.9	49
	9	9.8	583	529	10.2	49
	10	9.8	600	548	7.3	71
	11	9.8	570	517	7.5	65
	12	9.8	602	546	8.5	61
	13	15.0	568	517	8.5	57
	14	17.5	575	520	9.2	54
	15	20.0	576	513	9.5	52
	16	22.0	[a]511	[a]453	8.8	49
Channel-web beam 2	1	22.0	[a]587	[a]511	7.0	72
Corrugated-web beam 1	1	26.0	[a]587	[a]520	8.0	63
Corrugated-web beam 2	1	22.0	[a]614	[a]546	9.3	57
Truss-web beam 1	1	10.0	658	559	8.2	70
	2	22.0	[a]518	[a]457	6.6	66
Truss-web beam 2	1	15.0	576	502	7.3	68
	2	16.0	595	517	7.2	71
	3	17.0	592	515	7.6	67
	4	18.0	(b)	(b)	(b)	(b)
	5	19.0	594	516	8.4	61
	6	20.0	[a]583	[a]508	9.0	56

[a]Temperature at failure.
[b]No record.
[c]Average rate of change of maximum skin temperature.

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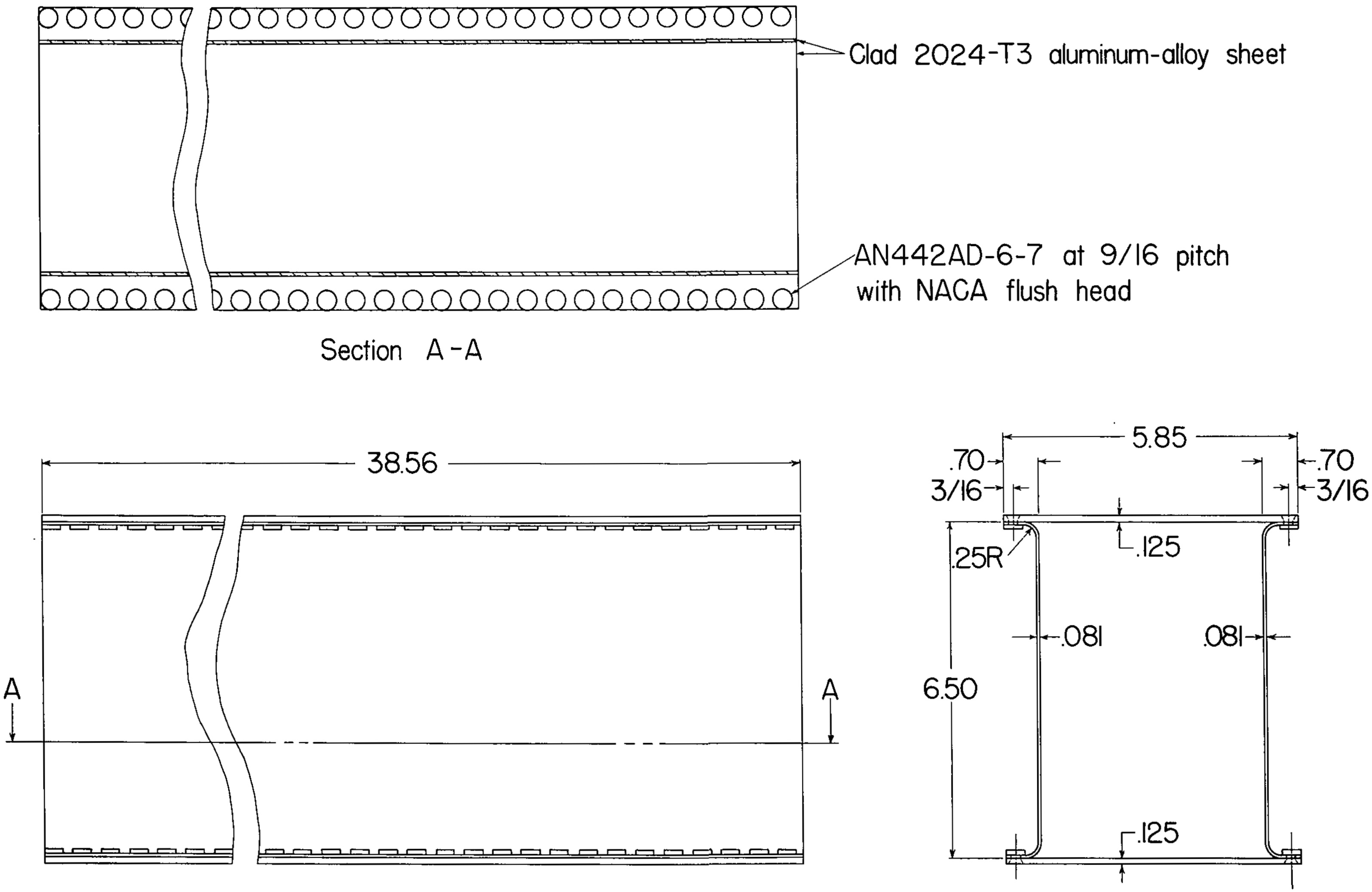

Figure 1.- Details and dimensions of channel-web beams.

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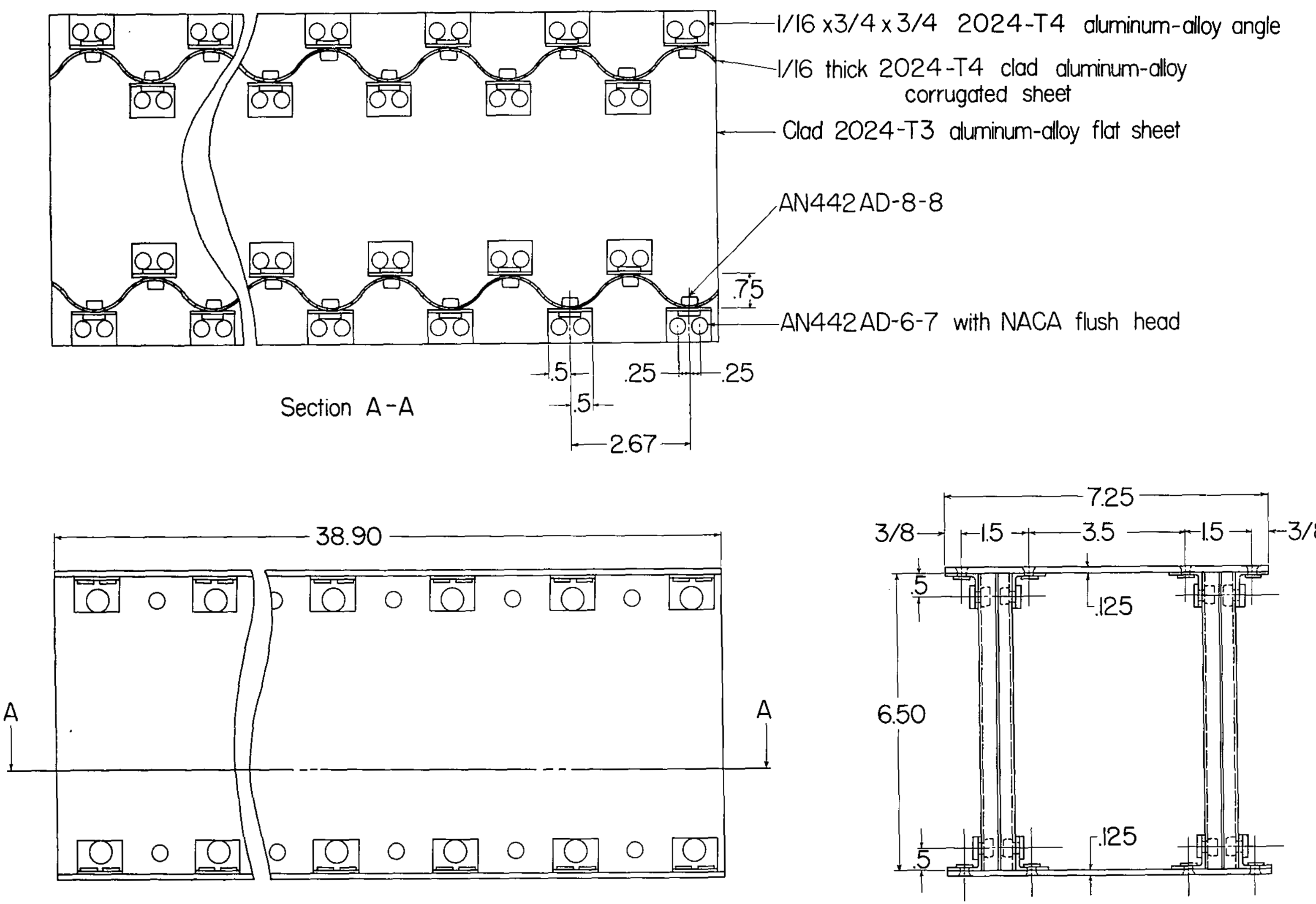

Figure 2.- Details and dimensions of corrugated-web beams.

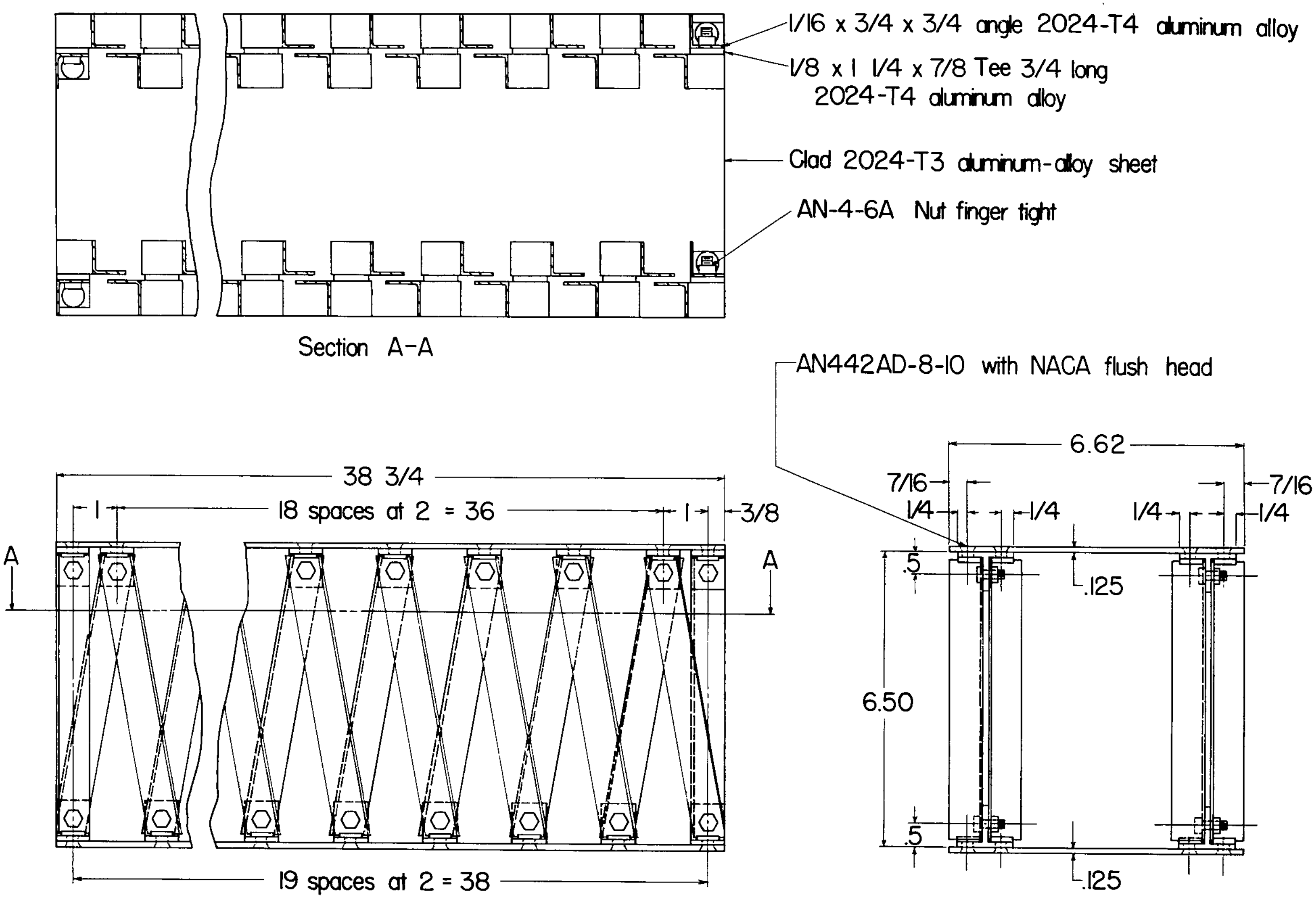

Figure 3.- Details and dimensions of truss-web beams.

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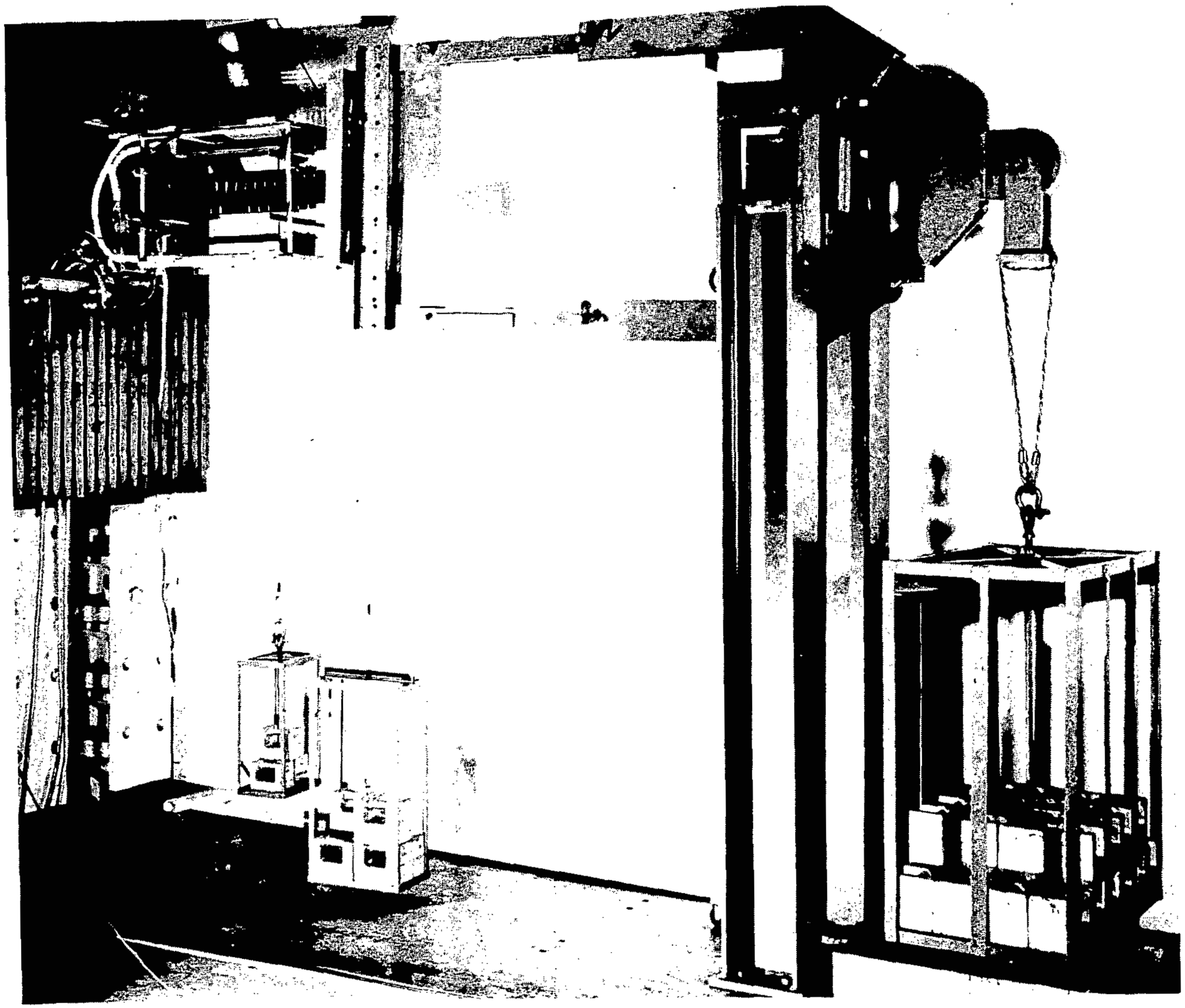

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Figure 4.- Static loading frame applying constant bending moment to truss-web beam.

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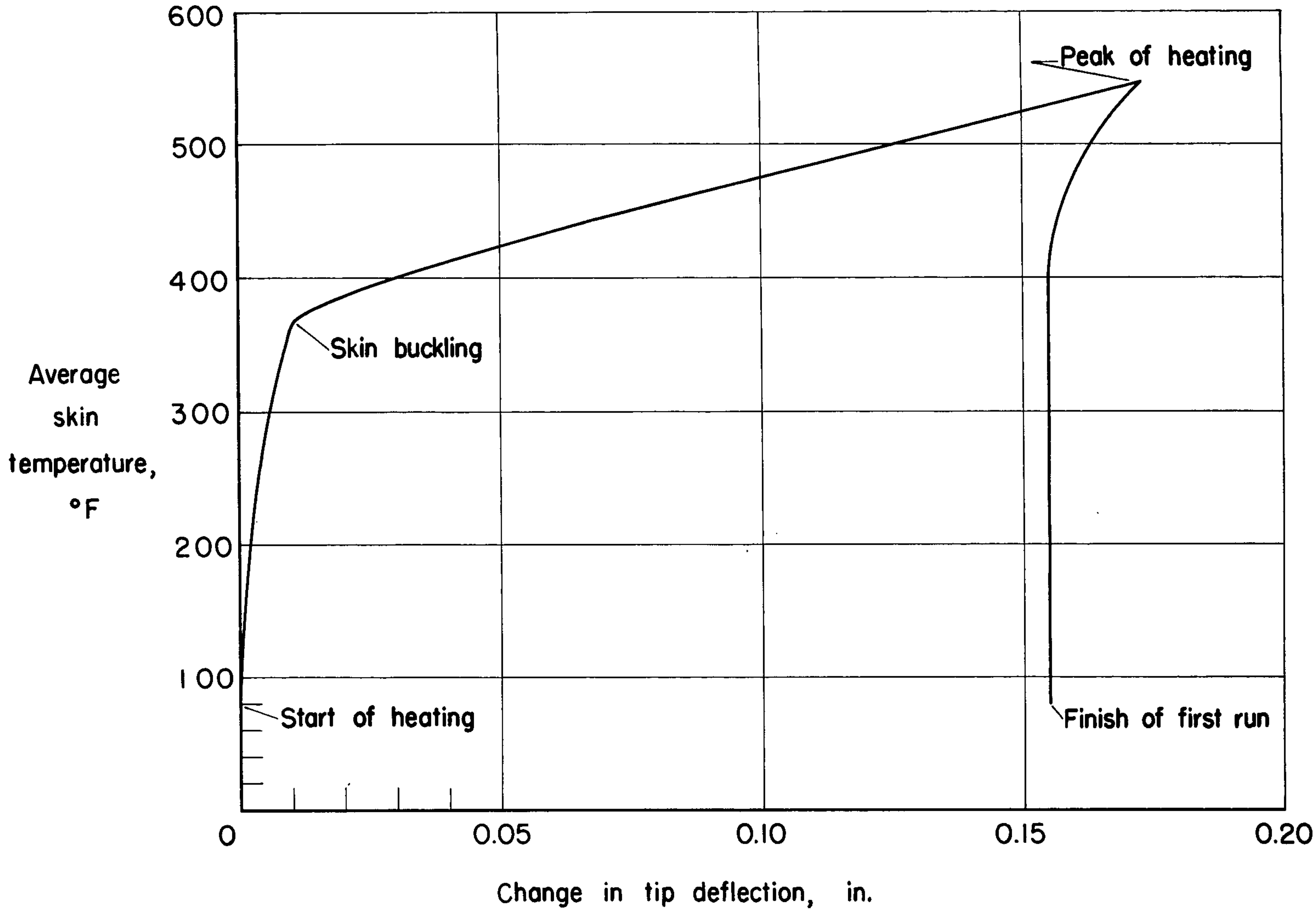

Figure 5.- Change in tip deflection with change in skin temperature. Channel-web beam 1; $\sigma_b = 9.8$ ksi, first cycle; rapid skin heating at 66° F/sec.

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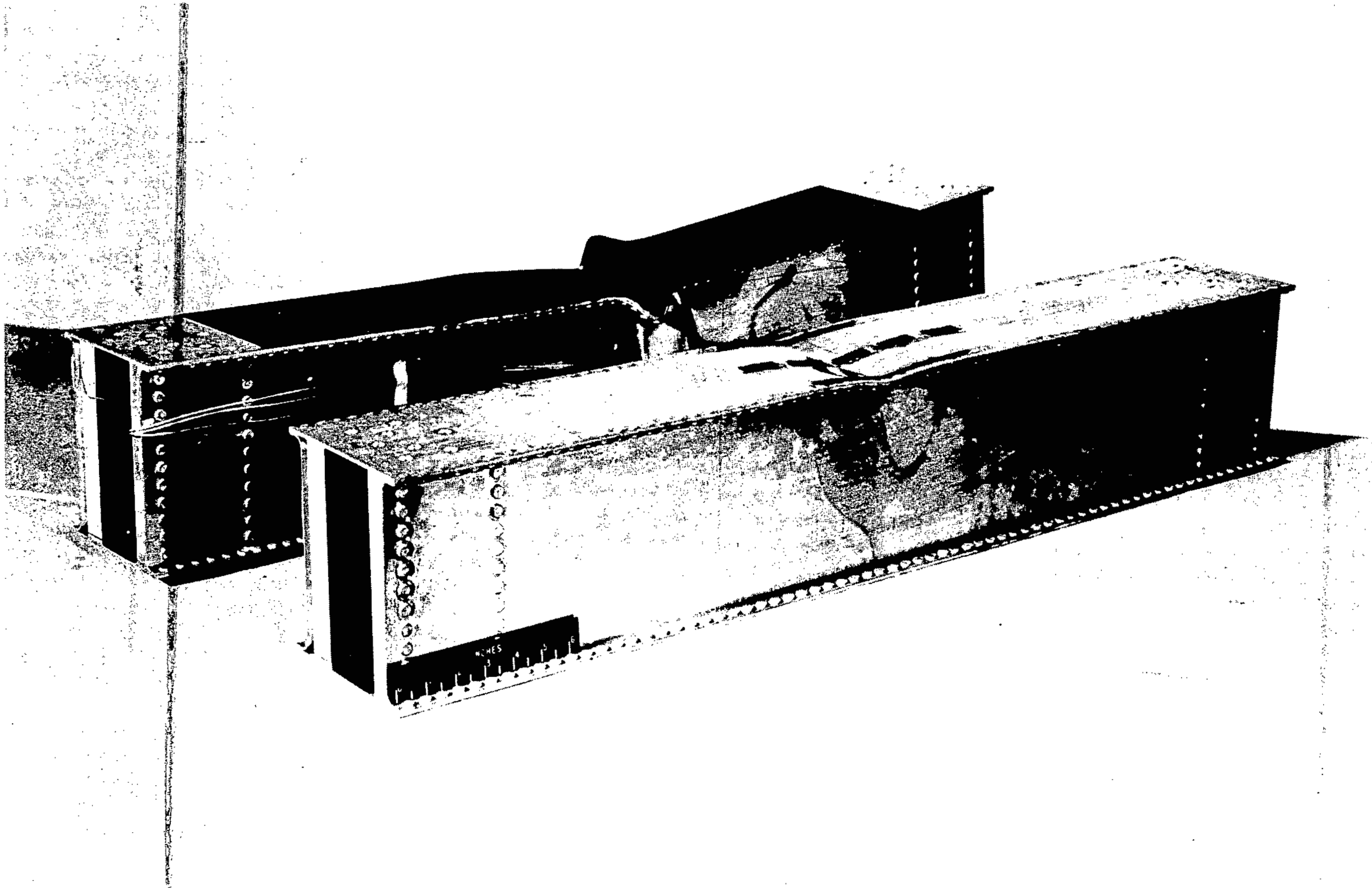

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Figure 6.- Bending failure of channel-web beams after rapid heating (painted skin) and at room temperature (unpainted skin).

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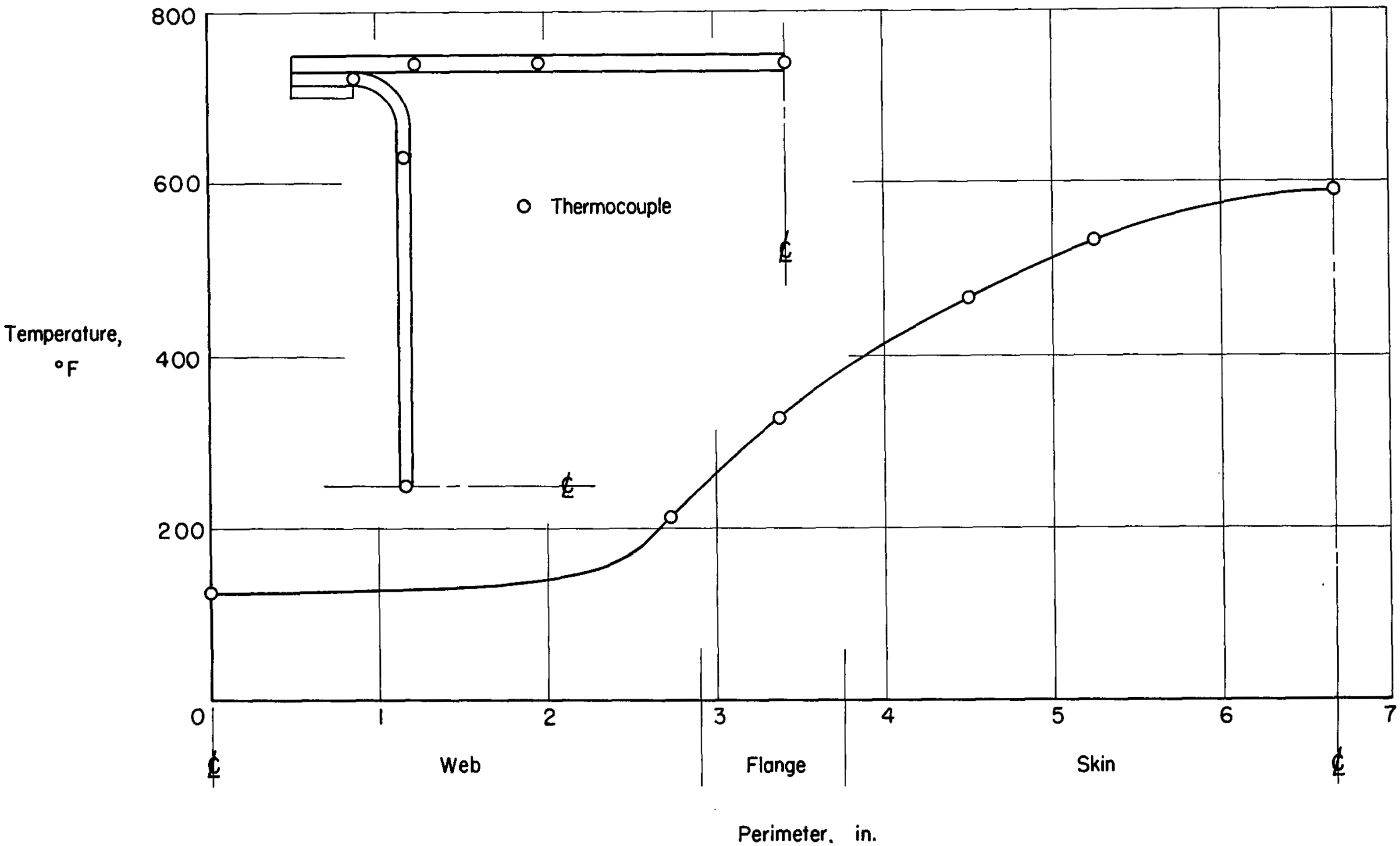

Figure 7.- Temperature distribution at failure in channel-web beam 2.
σ_b = 22 ksi; skin heating rate, 72° F/sec.

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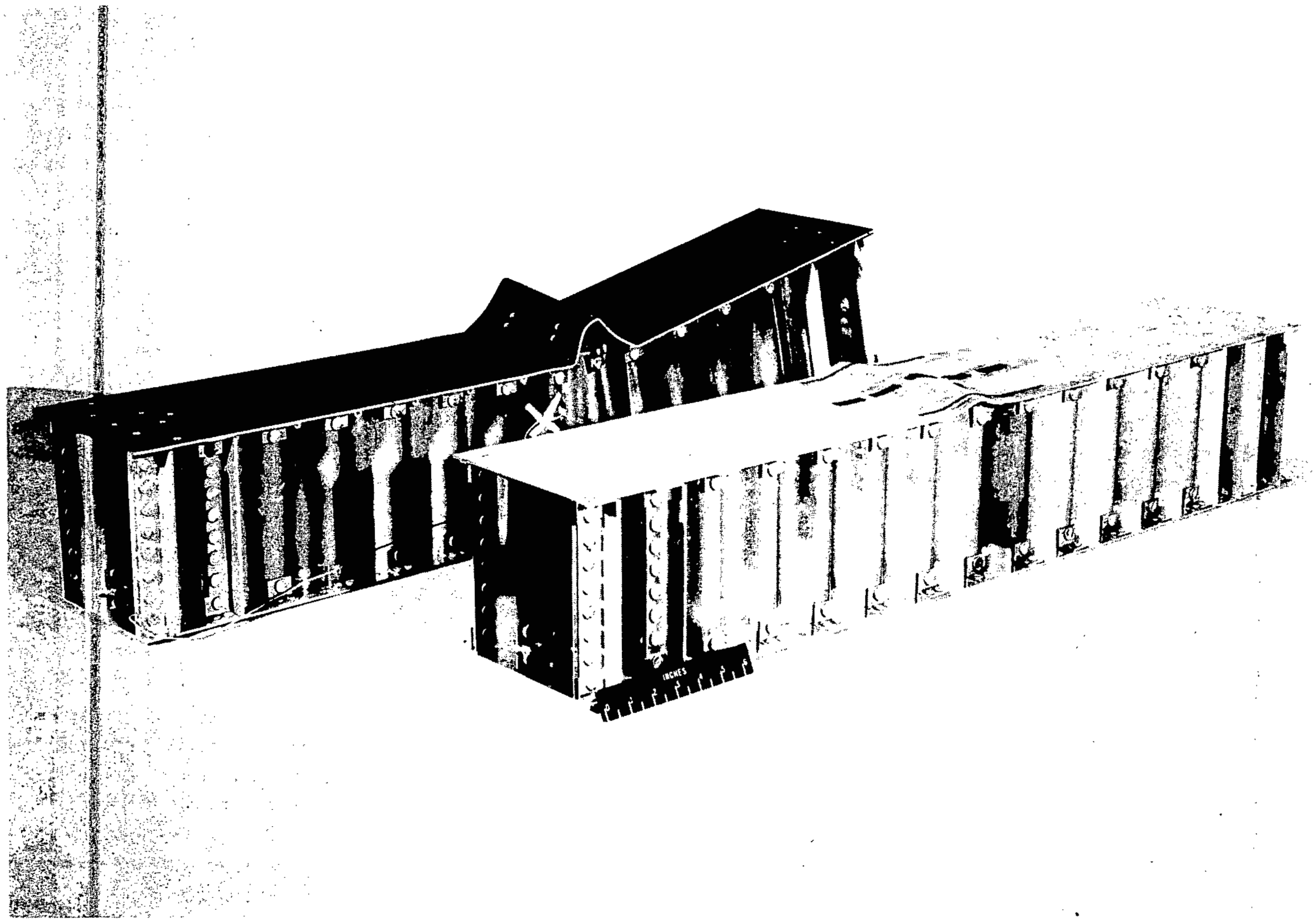

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Figure 8.- Bending failure of corrugated-web beams after rapid heating (painted skin) and at room temperature (unpainted skin).

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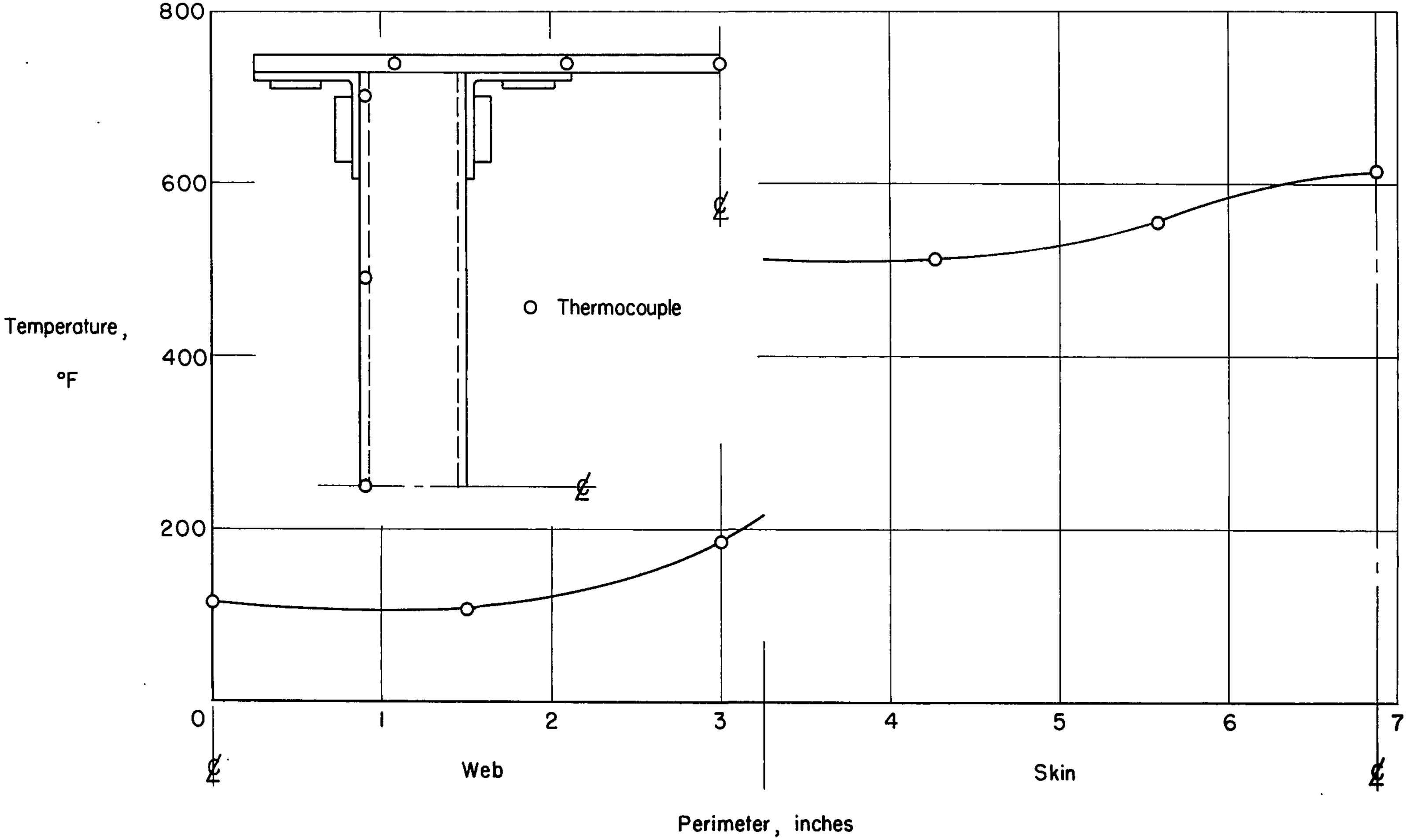

Figure 9.- Temperature distribution at failure in corrugated-web beam 2.
σ_b = 22 ksi; skin heating rate, 57° F/sec.

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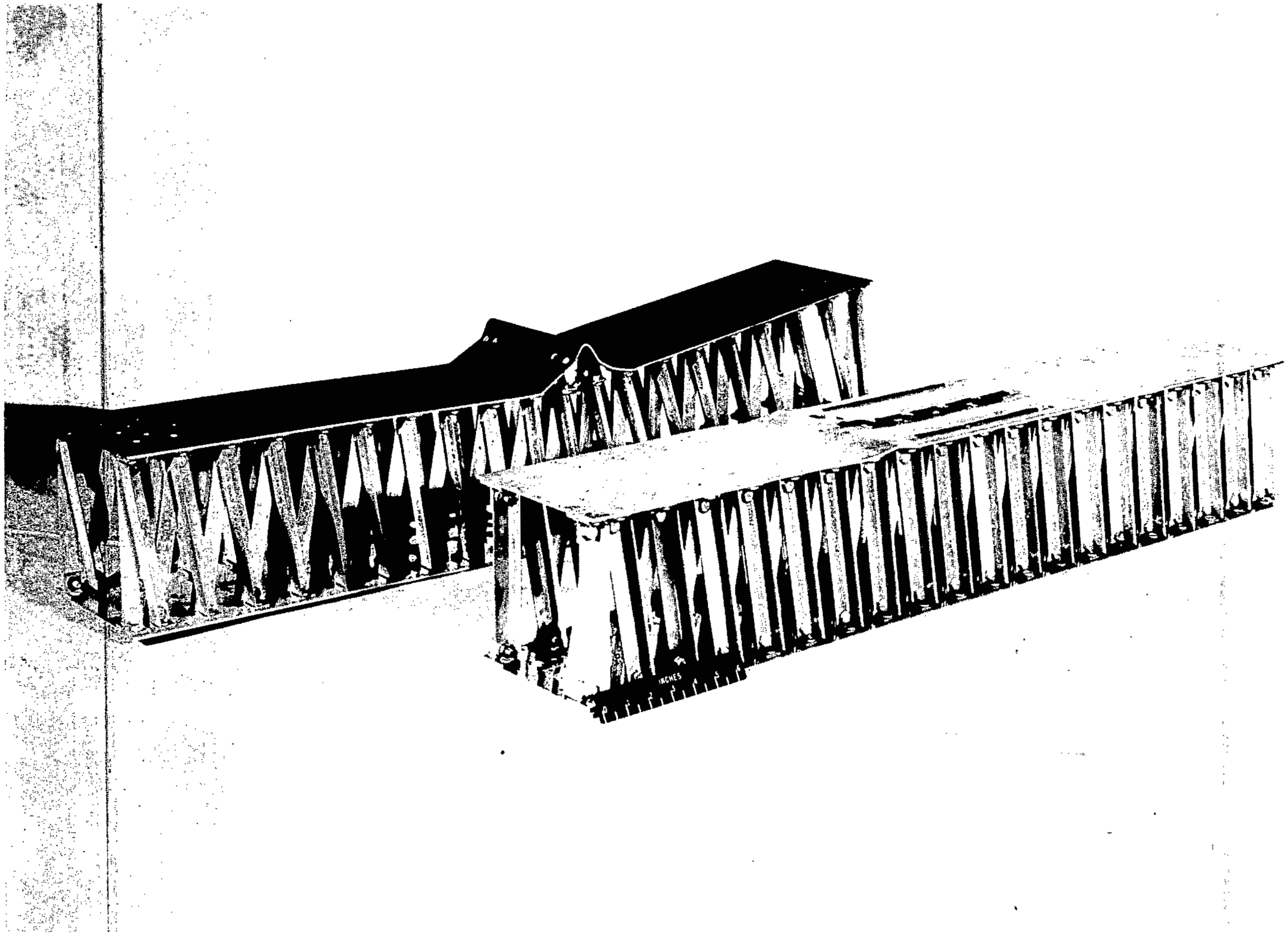

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Figure 10.- Bending failure of truss-web beams after rapid heating (painted skin) and at room temperature (unpainted skin).

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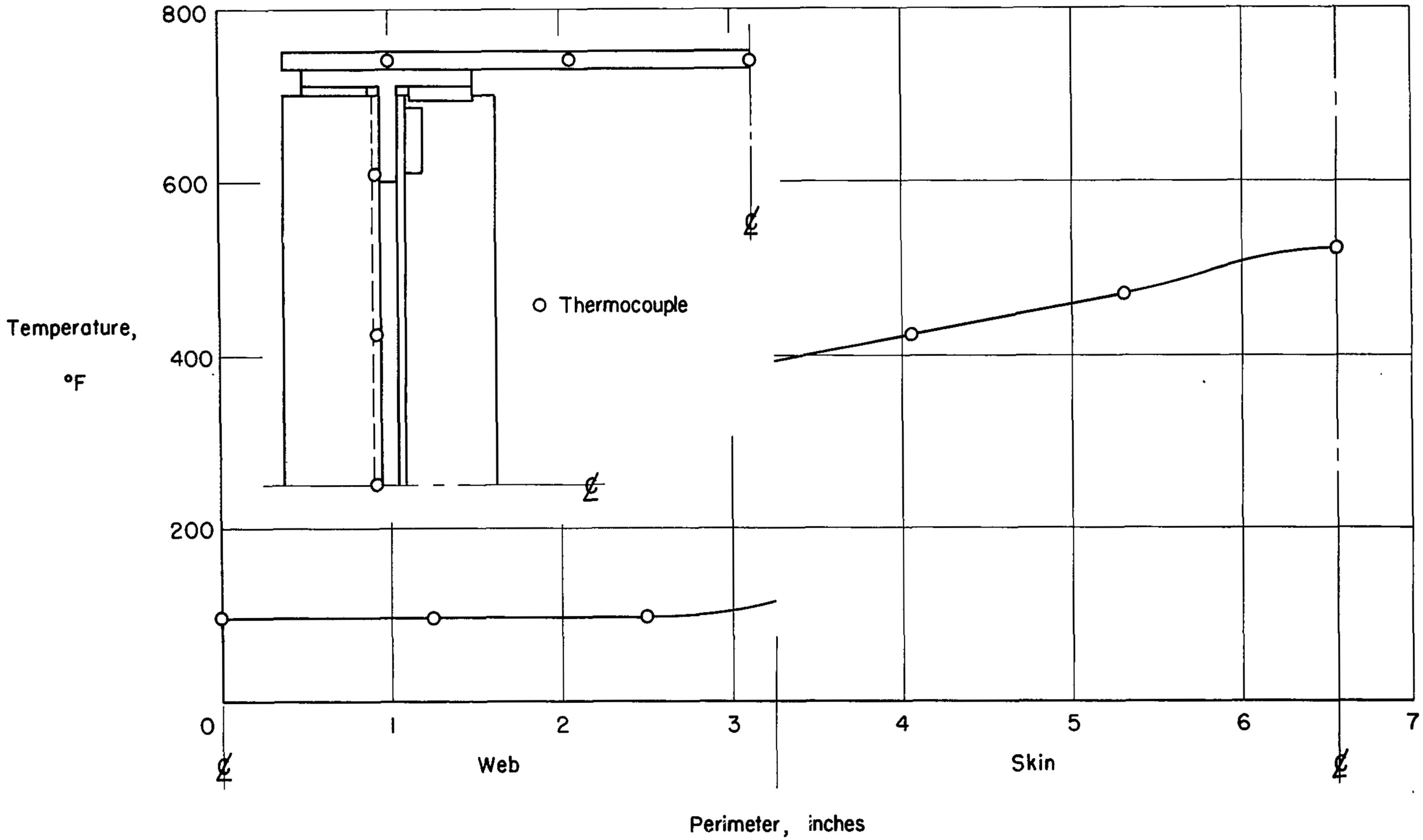

Figure 11.- Temperature distribution at failure in truss-web beam 1.
σ_b = 22 ksi; skin heating rate, 66° F/sec.

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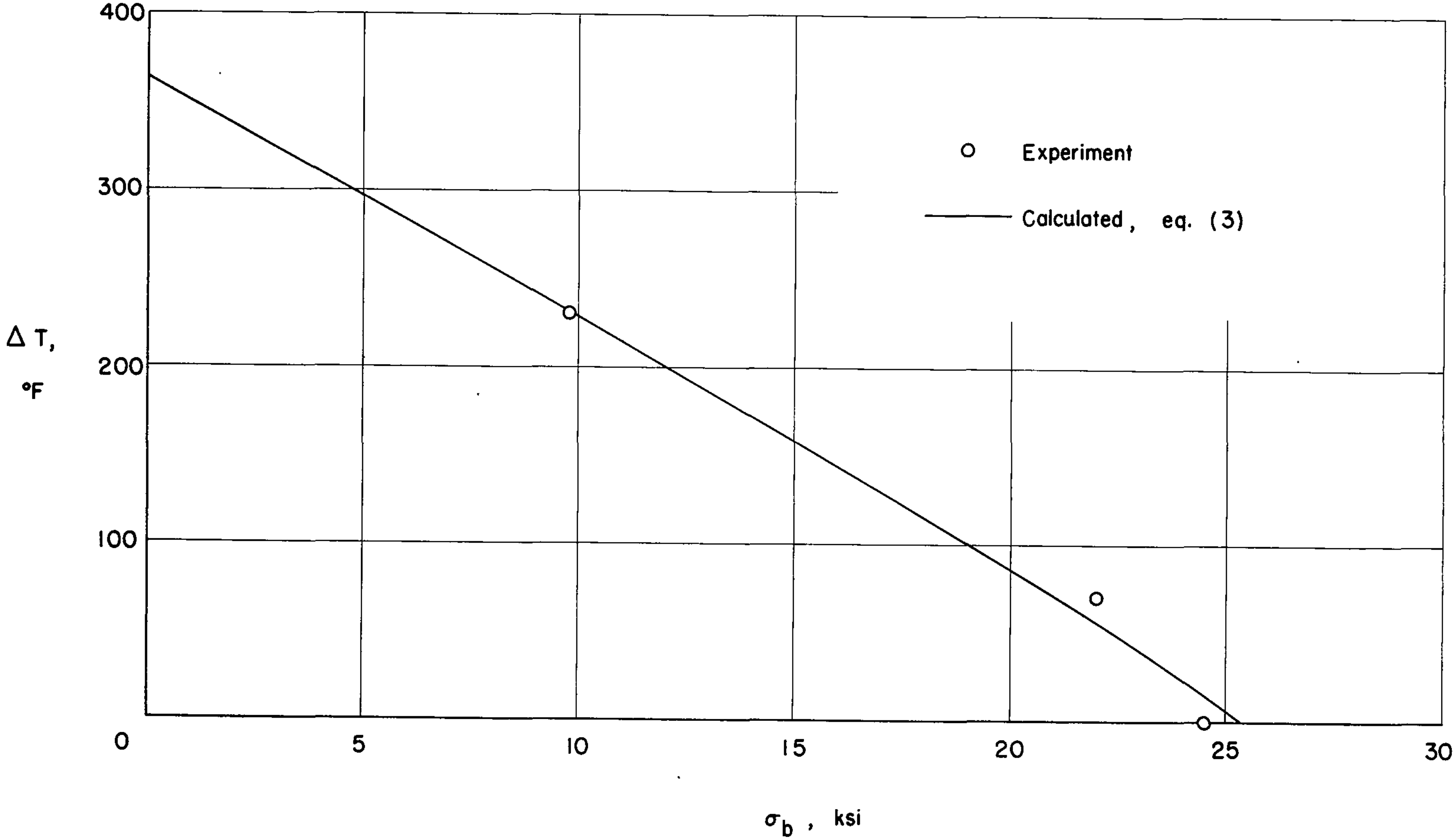

Figure 12.- Average temperature difference required to buckle skin of channel-web beams which are statically loaded in bending and subjected to rapid skin heating.

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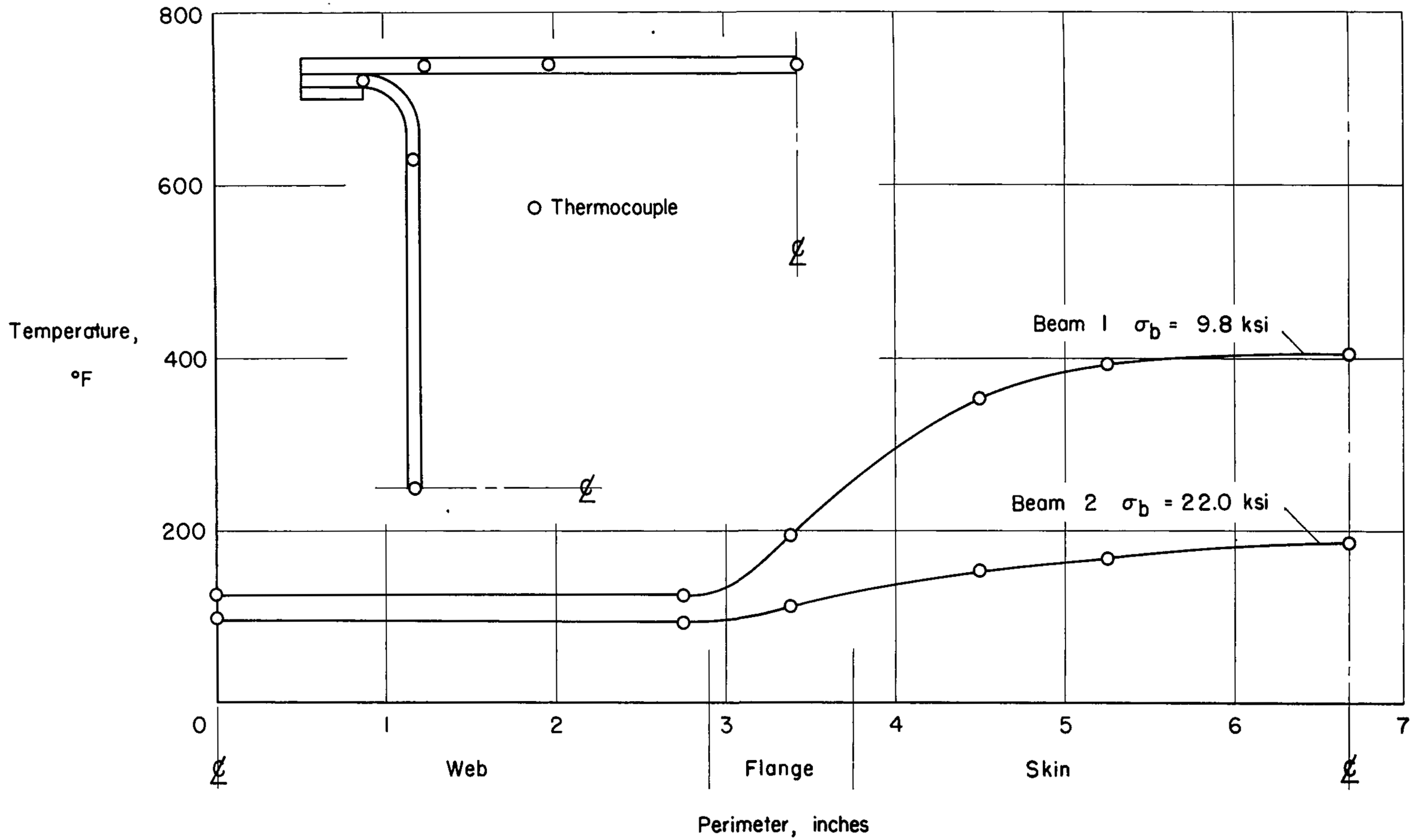

Figure 13.- Temperature distribution at buckling in channel-web beams.

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